LRL-102(Del.)

Photostat Price $ 18.30
Microfilm Price $ 6.00

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

STATUS OF THE MTA PROCESS

Issued February, 1954

LIVERMORE RESEARCH LABORATORY

OF THE U. S. ATOMIC ENERGY COMMISSION

OPERATED BY

CALIFORNIA RESEARCH & DEVELOPMENT COMPANY

LIVERMORE, CALIFORNIA

CONTRACT NO. AT(11-1)-74

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

This report summarizes the results of the MTA research and development program since presentation of the A-12 MTA plant concept in LWS-12300, issued in January, 1952. A new MTA plutonium production plant concept, C-50, is presented and compared to the previous A-12 concept. The numerous process improvements incorporated in the C-50 concept combine to increase the operability of an MTA plant as well as lower the estimated product cost from $230 per gram for A-12 to $124 per gram for C-50.

STATUS OF THE MTA PROCESS

1. INTRODUCTION

The electronuclear process for production of free neutrons, generally referred to as MTA, has been under development during the past four years by the University of California Radiation Laboratory and the California Research & Development Company. In 1950, the first Feasibility Report, LWS-18, was prepared by these organizations which described an electronuclear production installation. In that same year, construction was started at the Livermore Research Laboratory on a high current, low energy, experimental linear accelerator, known as Mark I.

The MTA process for production purposes requires two major units, an accelerator and a target. The accelerator produces a high-energy, high-current deuteron beam which is directed at the target. The target converts the deuteron beam into a stream of energetic neutrons which can be utilized for the production of desired materials through nuclear reactions. At various stages of development the MTA process has been considered for the production of plutonium, and U-233. The process appears capable of producing these materials.

The early development of the MTA process culminated in 1952 in the preparation of a production plant concept known as A-12. The A-12 concept was described in an MTA Status Report, LWS-12300, issued in January, 1952; this report was supplemented by Document No. LWS-24428, issued in June, 1952, which revised the A-12 concept in accordance with intervening developments. The A-12 linear accelerator was designed to operate at a frequency of 12 megacycles per second and was to consist of a vacuum vessel approximately 1500 feet long and 49 feet in diameter. As designed, the accelerator was excited by continuous wave rf power and produced a deuteron beam of 500 milliamperes current, 350-Mev energy, and about 30 inches in diameter. The A-12 target was designed to convert this beam into neutrons and in turn the neutrons were to be captured by uranium to form plutonium. As designed, the target consisted of three sections, a primary target, a secondary target, and a lattice, all of which contained uranium and were water-cooled. The estimated production from the A-12 plant concept was 564 kg of plutonium per year. Design and construction of the A-12 concept was authorized by the Atomic Energy Commission in October, 1950, and CR&D completed extensive construction engineering on this basis. However, in August, 1952, the Atomic Energy Commission cancelled the A-12 construction program and limited MTA work for an indefinite period to the experimental operation of Mark I and other experimental

programs. The California Research & Development Company accordingly has pursued a comprehensive research and development program to improve the MTA process over the A-12 concept. This program included operation of the Mark I linear accelerator from its completion in January, 1952 until its shutdown and dismantling, which started in December, 1953. The successful operation of this full scale low energy accelerator, together with the results of other experimental work has resulted in demonstrated practicality and significant technical and economic improvement in the MTA accelerator. Much theoretical and fundamental research on the MTA target has been completed also. While this lends assurance to the theoretical performance of the target, it is patent that the target has not been developed to a degree or on a scale commensurate with the accelerator.

This research and development effort has resulted in many significant changes and improvements in the MTA process as exemplified by the A-12 concept. A current MTA plant concept embodying these improvements, herein referred to as C-50, has therefore been prepared to evaluate these two years of MTA development.

2. SUMMARY

For the C-50 concept, the same production rate and the same site location were selected as for A-12 to facilitate comparison of the concepts. Tabulated are the major features of each concept.

	A-12	C-50
Production rate, kg/year	564	564
Accelerator		
Frequency, megacycles	12	50
Vacuum vessel		
Average dia., ft	49	11.75
Length, ft	1500	2650
Deuteron beam		
Current, milliamperes	500	320
Energy, Mev	350	500
Dia. of bore for beam, inches	30	6 to 9
Target		
Primary	depleted U	beryllium
Secondary	depleted U	depleted U
Lattice	depleted U	depleted U
Coolant	water	NaK for primary and secondary, water for lattice
Investment, millions $	427	212
Plutonium cost, $/gram	230	124

Decreases of 50 per cent in estimated investment cost and 46 per cent in the estimated product cost are primarily a consequence of the research and development efforts over the past two years.

While it is certain that continued research will result in further economic improvement of the process, it seems doubtful that unanticipated major changes will occur. It is therefore possible to make a good appraisal of MTA on the basis of the full scale operation of Mark I and the other experimental programs completed to date. Should this appraisal be favorable, the process is ready for full commercial development; if not, it is doubtful that further research can materially alter the evaluation and would be primarily of academic interest.

3. ACCELERATOR DEVELOPMENTS

The accelerator development program included not only the experimental operation of Mark I but the development of components of the accelerator and scale model development. For the sake of simplicity the results of these efforts are combined in the discussion below.

3.1 Results of Mark I Development Program

An accelerator suitable for the MTA process must have a consistent beam current of several tenths of an ampere at several hundred Mev energy. No previous accelerator had produced currents of this magnitude but if certain technical problems could be solved there was good possibility that such a machine could be a practical production device. The Mark I accelerator was therefore, built and experimentally operated to determine solutions to these technical problems. To prove the feasibility of an MTA accelerator beyond any doubt would have required building an accelerator of full energy as well as full current. However, the most important uncertainties could be answered by a much less expensive machine. It was decided, therefore, to build Mark I to the following specifications:

1. Pulsed beam current with eight, one-quarter ampere beam pulses per second and a 50 milliampere average beam.
2. Protons accelerated to 15 Mev or deuterons accelerated to 30 Mev.

The objectives of the Mark I developmental operation program included determination of:

1. Practicality of obtaining a vacuum of a billionth of an atmosphere in a vessel of about 225,000 cubic feet.

2. Feasibility of obtaining a sufficiently large current of ions collimated for injection into the machine and pre-accelerated to at least 100,000 electron volts.

3. Feasibility of exciting radiofrequency oscillations in the cavity without impractical measures to break through the "ion locks" anticipated at low voltage levels.

4. Feasibility of an electric system which could efficiently convert sixty cycle power from a power company transmission line to about 12 megacycle radiofrequency power in the accelerator cavity.

5. Feasibility of holding the necessary radiofrequency electric field gradients across the gaps between drift tubes and with large electrical energy storage in the cavity.

6. Feasibility of focusing the beam with magnets in the drift tubes.

7. Feasibility of obtaining acceleration of an adequate percentage of the injected beam and of avoiding damage to the machine from lost beam.

8. Reliability of operation of a machine of this size and complexity.

All of these objectives were attained, but, as one would expect, there were varying degrees of success in finding solutions. These are discussed below.

3.11 Vacuum

The vacuum problem though difficult was solved mainly through strict adherence to good high vacuum techniques. Pressures of 9×10^{-7} to 3×10^{-6}mm of mercury as measured in a liquid nitrogen trapped ion gauge and 1.5×10^{-6} to 5×10^{-6} by untrapped ion gauge were consistently maintained.

3.12 Ion Injector

An ion injector was developed which was highly satisfactory, except that it needs some improvement for sustained operation at high levels. It will inject either protons or deuterons at energies up to 100 kilovolts. It can be operated at any dutycycle from one or more pulses per second and five or more milliseconds per pulse to continuous direct current beam injection. Beam pulses with peak values of over two amperes into a 4-inch diameter accelerator bore are obtainable and one ampere peaks or better are normal. Continuous or average currents of about 0.5 ampere are readily obtainable but sustained operation for several hours at this level burns out internal electrodes and focusing grids. With a 40 kilowatt beam (e.g., 0.5 ampere at 80 kilovolts) the over-all injector efficiency is about one-third. (Although this figure is believed to be quite good it is not important in the over-all accelerator economics).

3.13 Accelerator Cavity Excitation System

Orginally the accelerator cavity was pre-excited with a system involving a separate power supply, separate oscillators and large rotating transmission lines and loops. (For a description of Mark I see report, LRL-60). Although the system worked, it was not practical. Later it was abandoned for a much better system involving no separate oscillators and rotating elements but still requiring a mechanical inductance shifting device which took about 10 seconds for each cycle of operation. These systems also required a sub-exciter power supply to maintain the cavity voltage above multipactoring levels between main power supply pulses.

The final radiofrequency power system provided ample voltage rise rates to permit pulsing the cavity from zero voltage without a sub-exciter power supply and without separate pre-excitation equipment. Performance of this latest system is discussed below.

3.14 Radiofrequency Power

The initial system for introducing radiofrequency power into the cavity included 16 self-excited oscillators using RCA-5831 tubes. Good performance was obtained from this system, but, as mentioned above, about 10 seconds were required to bring it into operation after a cavity spark or other fault had shut it down. With such faults occurring at very frequent intervals during radiofrequency "bakeout" of the cavity, these few seconds sometimes amounted to as much as 90 per cent of the total elapsed time. Thus the effective "on-time" was greatly reduced.

Prior to the last operating run, six of the oscillators were converted to amplifiers using RCA-2332 shielded grid tubes and driven by an auxiliary amplifier. The resulting system, with its independence of feed back drive, was a tremendous success. All excitation problems were eliminated. The voltage recovered almost instantly (a few milliseconds) from any energy dump due to cavity discharge or other cause. This not only made the rf on-time nearly 100 per cent of the time during which operation was attempted, but also made it possible to "bakeout" the cavity after evacuation in a fraction of the time previously required.

The last time the accelerator was evacuated it was only 27 hours from the time the Kinney vacuum pumps were started until a pulsed proton beam of about 0.1 ampere peak current was obtained on the target. These results are significant in that they demonstrate the practicality of realizing an operating factor well within that considered acceptable for production processes.

3.15 Accelerator Voltage Gradient Capacity

Since the mechanism of sparking in a resonant cavity is not well understood, one of the principle concerns prior to Mark I construction was that it might prove impossible to hold adequate rf voltage gradients across the gaps between drift tubes. Although the location of sparking was different than anticipated, this did prove to be by far the most serious problem which had to be solved to achieve satisfactory operation.

The drift tubes for Mark I were designed to require 22.5 million volts rf from end-to-end in the cavity for optimum proton acceleration and 45 million volts for deuterons. The gradients in the gaps between drift tubes were designed to be approximately 1.5 million volts per foot for proton acceleration.

In the larger gaps (one to three feet) it was found that after a large number of stored energy discharges, the drift tube surfaces "cleaned up" and held voltages better than 30 million volts end-to-end of the cavity without difficulty. These discharges varied from invisible X-ray bursts and pale gas glows to bright sparks emanating from a drift tube surface and branching out into space, but not arcing across to another surface.

In the smallest gap, of 4.2 inches, hot sparks arced across from one drift tube surface to the other at voltages as low as 17 million, and by the time the cavity voltage reached 20 to 22 million the damage to the surfaces was so great that shortly the voltage holding capacity fell to lower than the 17 million. Thus any beam operation of significant duration or at optimum voltage was prevented pending corrective measures.

While these measures were undertaken the first drift tube was removed and cavity voltages up to 33 million were obtained, as noted in the preceding paragraph, without any spark damage. This voltage was not maintained long enough to ascertain whether the frequency of discharges would diminish as the drift tube surfaces "cleaned up" but it was reasonable to expect that this would happen based on performance at lower voltages.

To clear up the trouble in the first gap, attention was first given to the surface material of the drift tubes. Tests on a low energy storage device indicated that both the spark frequency and spark damage could be greatly reduced by use of Inconel as first choice or OFHC (oxygen free high conductivity) copper as second choice. The original drift tube material was phosphorus deoxidized copper. A trial was made with Inconel surfaces, but its low thermal conductivity resulted in severe cracks so that only short-lived improvement was obtained. Later OFHC copper was used which was an improvement but not sufficiently so to solve the sparking problem.

It became clear, therefore, that the only real solution was to increase the length of the first gap. Since the system was designed for 100-kv deuteron or 50-kv proton injection and a 4.2-inch first gap, it was possible to relocate the drift tubes to give an 8.7-inch gap and inject protons at a higher energy. The optimum injection energy for this gap proved to be 66 kv. In order not to lose too much beam in the gap it was necessary to install a focusing magnet just outside the end wall of the cavity. Even with this modification the beam acceptance was poor, partly because the bore of the first tube should have been larger at this distance.

With the 8.7-inch minimum gap the cavity voltage, without beam, could be run up to 25 million volts at will. No effort was made to explore the upper limit or to further increase the gap since it appeared that more injection voltage would be necessary for significant deuteron beam operation even if the necessary rf voltage proved feasible.

It was possible after evacuation to accelerate greatly the surface outgassing and subsequent "clean up" by heating the drift tube and cavity surfaces with hot water for several hours.

3.16 Beam Focusing

Previous low current linear accelerators overcame the beam de-focusing effects of space charge and rf fields by such methods as shaping the fields with grids across the drift tube bores and/or merely tolerating a very large beam loss. Since grids would burn out at large beams and large losses would defeat the objective it was decided to overcome the de-focusing forces with solenoidal magnets in the drift tubes.

This method of focusing in Mark I was quite satisfactory and it was found that the magnetic fields were not critical beyond the first two or three magnets. Even these did not have a well defined minimum value. Factors such as the disproportion resulting from the increased length of the first gap and the small number of resonant cells in Mark I make it difficult to extrapolate any data to determine minimum field requirements or probable beam losses for an accelerator of several hundred Mev. In fact no significant correlation with theoretical beam dynamics was obtained. (The determination of minimum field requirements is not important to the over-all economics of the MTA, but any significant beam loss at high energy would be serious).

3.17 Mark I Beam Currents

After correcting the voltage holding problems it became possible to accelerate proton beam at will up to a maximum of about 225 milliamperes of peak beam in short pulses at pulse rates up to 8.2 per second, or continuous wave beams up to 50 milliamperes for short periods. Since the reset mechanisms were not designed for continuous wave operation, and pulsed operation was more stable, most operation was pulsed, with duty cycles in the range of 20 to 60 per cent. Average beams of as high as 100 milliamperes were obtained for periods of a few minutes. A 50 milliamperes average beam could apparently have been held indefinitely if the injector could stand it. In spite of the injector sparking, a beam on the target of 50 milliamperes average was accelerated over a period of 13 hours.

At average beams on the target above about 50 milliamperes the accelerator became unstable in voltage holding, apparently due to the large portion of injected beam which was not accelerated and which was largely lost in the first two gaps. No significant material damage resulted from the lost beam. Only a little over ten per cent of the injected beam reached the target. This was due to the small percentage of the continuously injected ions which crossed the large first gap during a portion of the rf cycle which would result in their being accelerated in synchronism with the balance of the machine.

The amount of beam accepted by the accelerator could be greatly increased by a more optimum arrangement of injection velocity, gap length, and cell length, and by injecting a beam modulated to match the rf cycle in the first gap. Presumably the beam on the target could thereby be increased by a large factor for a given amount of tolerable lost beam, but these alterations were not made on Mark I.

The above beam currents were measured on the target without regard to beam energy. Measurements of beam through foils indicated that roughly 75 to 80 per cent of this beam was above 10 Mev. With the modified drift tube arrangement the theoretical value should be roughly 12 Mev. These energy measurements had to be taken at low beam currents, but it is assumed that they would be as good, or better, at high beam currents.

3.18 Operating Reliability

Mark I never operated steadily with beam for more than a few hours at a time. However, the operating factor improved tremendously and continuously throughout the life of the machine. Furthermore, the nature of the program necessitated making constant changes, and economy prevented making many improvements aimed primarily at further reliability after the lost time was reduced to relatively minor proportions. In the last days of operation, with the new amplifier system, the only extensive lost time was due to the inability of the present injector to handle the high beam levels being attempted on a sustained basis. At lower beam levels, or with a re-engineered injector the reliability should have been very good.

3.2 Current MTA Accelerator Concept

In reviewing the significance of the Mark I results and particularly their relation to an accelerator for an economic MTA process, it is evident that the factors of voltage gradient, frequency and injection voltage are most important. They are also interdependent.

Voltage gradient determines the length of the accelerator for a given final energy of the accelerated particles. Thus, as high a gradient as compatible with other considerations is desired in order to keep down the length of the machine. But operating costs for electric power become greater as the voltage gradient is increased because the consumption of power for cavity skin losses increases.

The resonant frequency of the cavity is determined by its diameter and as small a diameter as reasonable is desired to minimize capital and operating costs. In the design of Mark I the diameter was fixed by the then existing technical knowledge of beam focusing, and of electronic tubes capable of high power output at high radiofrequencies. Tubes had been developed and

used for much higher frequencies than 12 megacycles but their time average power output per tube was so small that an impractical large number would have been required to supply the necessary power.

The stage of technical knowledge at the time of Mark I design indicated that the one-quarter ampere beam would need about a two and one-half foot diameter hole or drift tube bore. So a three foot bore was selected to allow for any misalignment of drift tubes or imperfections in focusing. This size bore together with the space needed for the magnet set the minimum size of the drift tube which, in turn, placed a limit on how far the diameter of the cavity could be reduced below that of Mark I. Even though this factor was not important in Mark I design it now is significant because of the advances in electronic tube technology. But solenoidal magnets did a much better job of focusing the beam than was first expected. Consequently a greatly reduced drift tube bore diameter is now feasible.

Even more important, however, are the developments of the shielded grid electronic tube (RCA-2332) and the greatly improved knowledge of the associated circuits required for the rf power system. Such developments have made it reasonable to consider frequencies in the order of 50 megacycles or higher. The advantages to be gained in this direction are illustrated in Fig. 1.

Brookhaven strong focusing was carefully considered for application to the beam problem and a few tests were made on the injector test setup. It appears that the advantages are not as great as anticipated partly because the solenoidal method proved to be better than expected. Furthermore, each strong focusing magnetic lens would need to be different from all others. Also present evaluations indicate that the accuracy required in fabrication, adjustment, and operation of the lenses would be so stringent that any advantages over the solenoid type would be cancelled. In any event, as discussed more thoroughly in Section 5.2, the incremental economic gain by further reduction of beam diameter for the sake of increased frequency over 50 megacycles approaches a marginal region.

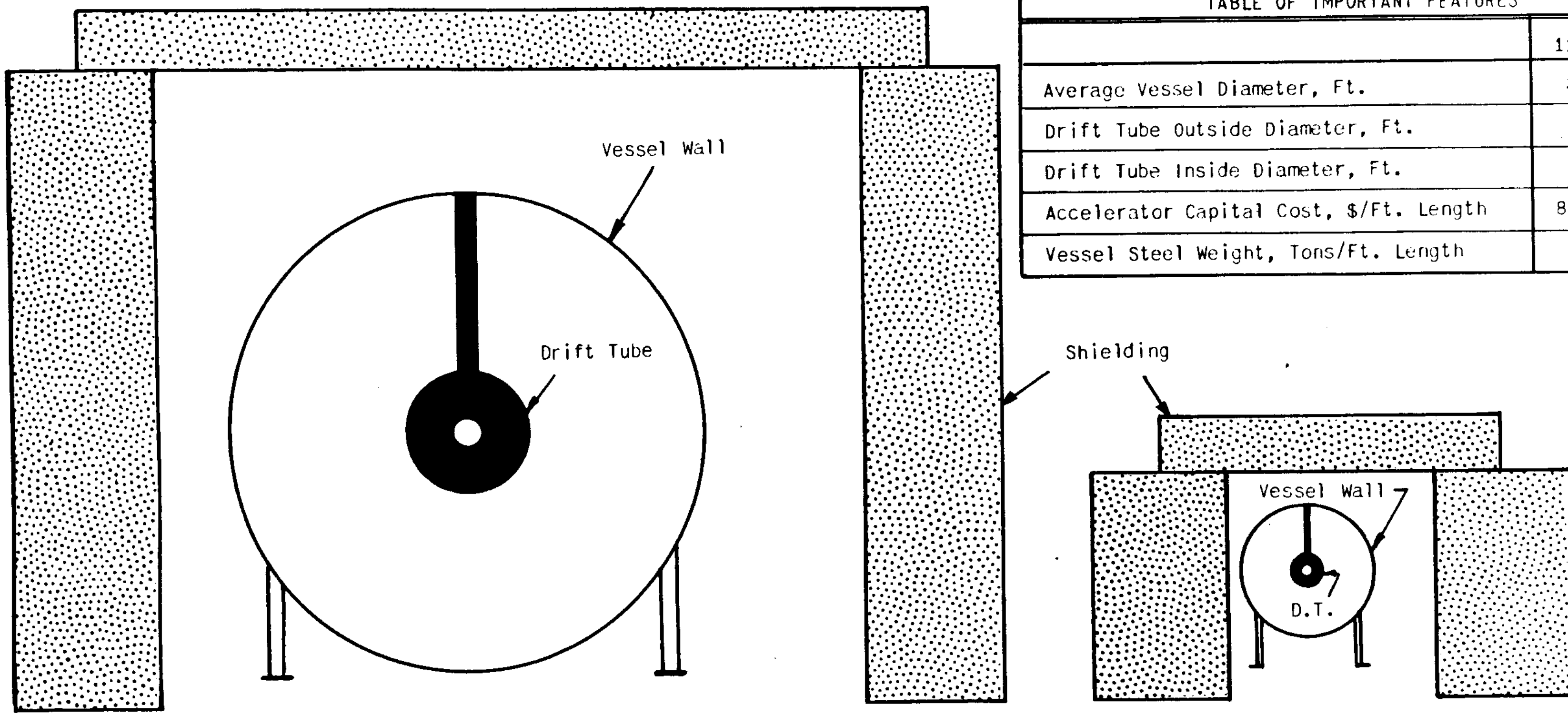
A further advantage of a smaller beam than thought possible during the design of Mark I, is the smaller target and beam hole in the target. This is also more thoroughly discussed in Section 4.2.

Mark I results showed that for a given voltage gradient and frequency there was a minimum first gap length that could be tolerated if destructive type of sparks were to be avoided. Of course the longer the first gap, the greater the injection voltage required to start the ions on their trip through the accelerator. Injection of a high current beam at something like one or two Mev does not present an insurmountable technical problem. But it certainly seems reasonable to expect an ever increasing first cost and more difficult technical problems as higher and higher injection energies are considered.

16

TABLE OF IMPORTANT FEATURES

	12Mc	50Mc
Average Vessel Diameter, Ft.	49.7	11.8
Drift Tube Outside Diameter, Ft.	8.33	2.05
Drift Tube Inside Diameter, Ft.	3.00	0.50
Accelerator Capital Cost, $/Ft. Length	81,700	23,600
Vessel Steel Weight, Tons/Ft. Length	5.00	0.86



TYPICAL SECTION OF 12 MEGACYCLE ACCELERATOR

TYPICAL SECTION OF 50 MEGACYCLE ACCELERATOR

FIG. 1 - SIZE COMPARISON OF 12 AND 50 MEGACYCLE ACCELERATORS

4. TARGET DEVELOPMENTS

A continuing MTA target development program has been carried on since the issue of the last MTA Status Report, LWS-12300. This program has adapted the applicable new knowledge from the related reactor development program and has experimentally and theoretically developed the unique phases of the MTA process to obtain basic target design data.

Although the MTA process can be used to produce other materials, the recent program has concentrated on the production of plutonium from depleted uranium. The function of an MTA target for plutonium production is to convert the beam of accelerated deuterons into a substantial quantity of free neutrons which are subsequently captured by U-238 atoms to form plutonium. This process is regarded as occurring in three steps and essentially in three separate target sections. These are:

(a) Primary Target:	Converts the deuteron beam into a stream of very high energy neutrons.
(b) Secondary Target:	Multiplies these energetic neutrons into a stream of less energetic neutrons with some attendant production by bombardment of uranium fuel.
(c) Lattice:	Produces additional plutonium from the neutrons available from the secondary target by capture in additional uranium fuel with possible further neutron multiplication.

Since the best MTA target design is the one which results in the lowest product cost, the objective of target development is to obtain a workable concept which produces the maximum number of free neutrons per unit cost. In order to accomplish this objective, the yield of neutrons per incident deuteron and the attendant cost have been studied in relation to the many possible target variables. These variables include the shape, size, arrangement, and number of target units. Other variables are the energy and size of the deuteron beam and the choice of primary target material, structural materials, and coolants.

The results of the MTA target development program and the resulting improvement of previous target concepts are discussed in this section.

4.1 Neutron Production Characteristics of MTA Targets

One of the most important phases of the MTA target development program has been to develop the production characteristics of MTA targets for reasonable values of the possible variables. The variables which have the greatest effect upon production are the beam energy, the choice of primary material, and the choice of coolant. Hence, these have been selected as the principal variables for the studies summarized below. In order to normalize the results of these studies, all yields are reported as total number of neutrons produced per incident deuteron.

While the MTA process is expected to be most economical at deuteron beam energies of about 500 Mev, the UCRL synchro-cyclotron will accelerate deuterons at present to only 190 Mev. Most of the experimental data have been obtained on this machine, although some data have been obtained for 230-Mev deuterons from the University of Chicago cyclotron. Lacking high energy experimental yield data, the approach has been to use the low energy experimental results to check theoretical methods of predicting neutron yields for various targets over all ranges of the beam energy. While additional experimental research at higher deuteron energies is required for obtaining exact design data, it is felt that the present methods of calculating neutron yields at higher energies give conservative results.

4.11 Experimental Yield Measurements

A considerable quantity of experimental yield data have been obtained using the UCRL synchro-cyclotron and some additional data have been obtained from the University of Chicago cyclotron.

Yield measurements have been made on targets one and two feet square. These dimensions are large compared to the experimental deuteron beam diameter of approximately two inches. The yield of neutrons which escape the target assembly, the "external yield", is measured by a calibrated manganese sulphate tank surrounding the target. The radioactivity resulting from neutron capture in manganese is used as the detector. Those neutrons which are captured in the target, the "internal yield", are measured by radiochemical methods.

Experimental yield measurements clearly indicate that the presence of water as a coolant in the secondary target reduces the yield appreciably as compared to liquid metal coolants. Hence, most of the experimental work has been carried out with liquid metal coolants.

Much information can be obtained from yield measurements made on solid, or uncooled, targets. This simplification can be used particularly with respect to the selection of suitable primary target materials. Examples

of the experimental data from which the primary target material can be selected are given in Tables I, and II.

TABLE I

Total Yield Measurements for Various Primary Target Materials

(One foot square targets; uranium secondary target, 190-Mev deuterons)

Primary Target Material	Yield, Neutrons/Deuteron		
	Internal	External	Total
U	0.6	3.2	3.8
Be	0.8	2.9	3.7

Table I points out that beryllium as a primary target material is not as efficient as uranium. However, as discussed in a later subsection, other considerations tend to equalize this difference.

Table II compares the external yield of beryllium primary targets with those of still other primary materials.

TABLE II

External Yield Measurements for Various Primary Target Materials

(Uranium secondary target; 190-Mev deuteron beam)

Primary Material	External Yield from Secondary Target, neutrons/deuteron
Be	2.90
Li	2.74
C	1.80
Al	1.75
H_2O	1.27

Thus, both beryllium and lithium appear to be possible primary target materials. An objection to the use of lithium is the probable necessity of using separated Li-7 to avoid the tritium contamination from Li-6.

Some experimental data showing the energy dependence of the yields have been obtained for both uranium and beryllium primary targets from high energy deuteron beams obtained with the University of Chicago cyclotron. These data are given in Table III and pertain to 4-1/2 inch diameter primary targets backed by one foot square uranium secondary targets.

TABLE III

Energy Dependence of External Yield		
Primary Material	External Yield with 190-Mev Deuterons	External Yield with 230-Mev Deuterons
U	3.2 neutrons/deuteron	5.1 neutrons/deuteron
Be	2.9	4.2

Table III shows clearly that production is greatly increased by increases in beam energy. Experimental facilities are not yet available, however, for the experimental determination of yields at higher energies. The theoretical prediction of yields for various target combinations at higher energies is discussed in the following subsection. These theoretical calculations are checked against the 190 and 230-Mev data discussed above.

4.12 Theoretical Yield Calculations for High Energies

Since the MTA process is expected to be most economical at deuteron beam energies of about 500 Mev, and experimental yield data are limited to energies of 190 and 230 Mev, calculations must be used to predict the neutron yield at these higher energies. The lower energy data serve to check the validity of the calculations. The methods of theoretical calculation of the neutron yield from the primary target and the multiplication incurred in the secondary target are discussed below.

The mechanism of neutron production in uranium bombarded by high energy particles has been investigated theoretically in sufficient detail that confidence may be placed in the predicted yields. Qualitatively, the mechanism may be described as follows. A high energy particle reacts with a nucleus, transferring part of its energy to the nucleus and knocking out one or more high energy particles. The excited nucleus then decays to a ground state by neutron emission. These "boiled-off" particles are of energies such that they may produce additional fission in U-238. The particles "knocked out" of the nucleus can repeat the initial process but with lower yields due to their lower energies. The yield, then, is the sum of all the neutrons produced in these events. Yields have been evaluated on the basis of theory for neutrons, protons and deuterons on uranium. It is felt that the mechanism of neutron production in uranium-uranium targets, and of neutron multiplication in the uranium secondaries for light metal targets, are fairly well understood.

A considerable effort is now being directed to the calculation of yields from light metal primary target systems. These have not as yet been placed on as firm a basis as the uranium system, so that the results presented

here must be considered preliminary. The interaction of deuterons with a light metal nucleus has been analyzed into stripping and knock-on events. From an estimation of nuclear transparency to incident nucleons, one can calculate the interaction cross sections that (a) both deuteron nucleons proceed, independently, beyond the interacting nucleus (b) that one nucleon interacts with a target nucleon while the other proceeds, and (c) that both nucleons interact with target nucleons.

In the present calculation the distributed deuteron interactions of this sort within the primary target have been normalized to the interaction of a single deuteron having a properly weighted effective energy. The probability of this interaction occurring is taken to be the calculated interaction probability for a deuteron traversing the primary target. The numbers and energies of neutrons arising from this interaction are then corrected for their interactions in escaping from the target. These neutrons are finally multiplied in the secondary uranium target in the manner described above for a uranium-uranium system.

From the experimental work of Hofmann and Strauch (Phys. Rev. 90, 449, 1953) it is apparent that the "extra" neutron in beryllium must receive special consideration. Thus in one-ninth of the nucleon-nucleon interactions between a deuteron and a beryllium nucleus, this neutron was considered to be ejected with the energy of the incident nucleon. In all other interactions in beryllium, and in the other light metal targets considered, the incident and struck nucleons were considered to share the incident nucleon's energy equally.

It is believed that the method of yield calculation presented for light metal primary targets predicts the energy dependence of neutron yield quite well. It should not be expected, however, to predict absolute yields. Thus a normalizing factor was determined which matched the calculated beryllium-uranium yield to the experimental yield at 190 Mev. This same factor was then applied to all of the other light metal systems studied. The results for uncooled uranium-uranium and light metal-uranium target systems are presented in Fig. 2. The effect of NaK cooling of uranium-uranium and beryllium-uranium targets is shown in Fig. 3.

4.2 Recent Developments Affecting Design of Target

The A-12 target concept presented in the last status report (LWS-12300) employed depleted uranium in the primary, secondary, and lattice sections. It used light water both as a coolant and a moderator, and was designed to utilize a relatively large diameter deuteron beam. That early concept was selected as the most feasible at that time, based on the meager experimental data available.

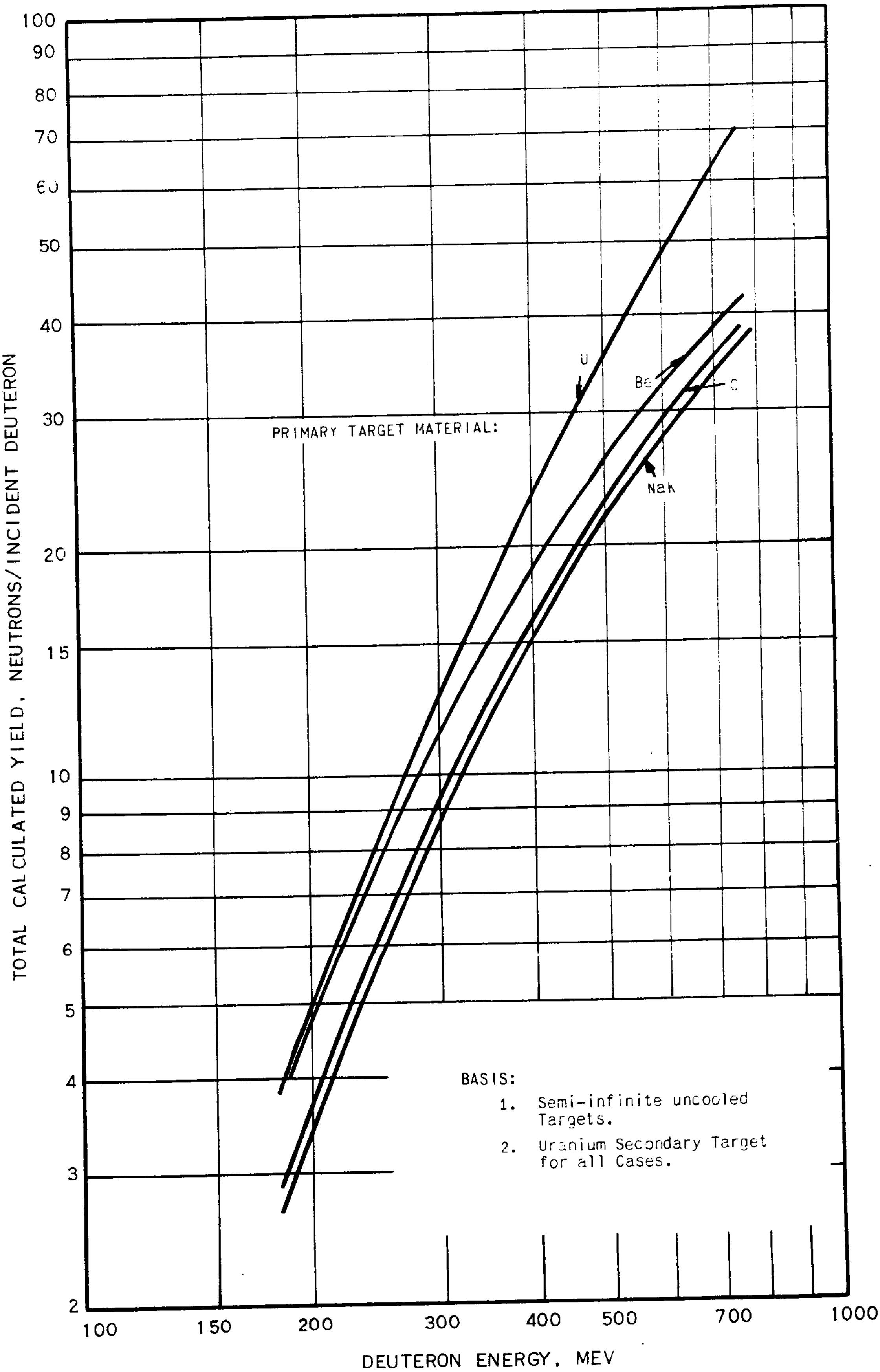


FIG. 2 - PREDICTED NEUTRON YIELDS WITH VARIOUS PRIMARY TARGET MATERIALS.

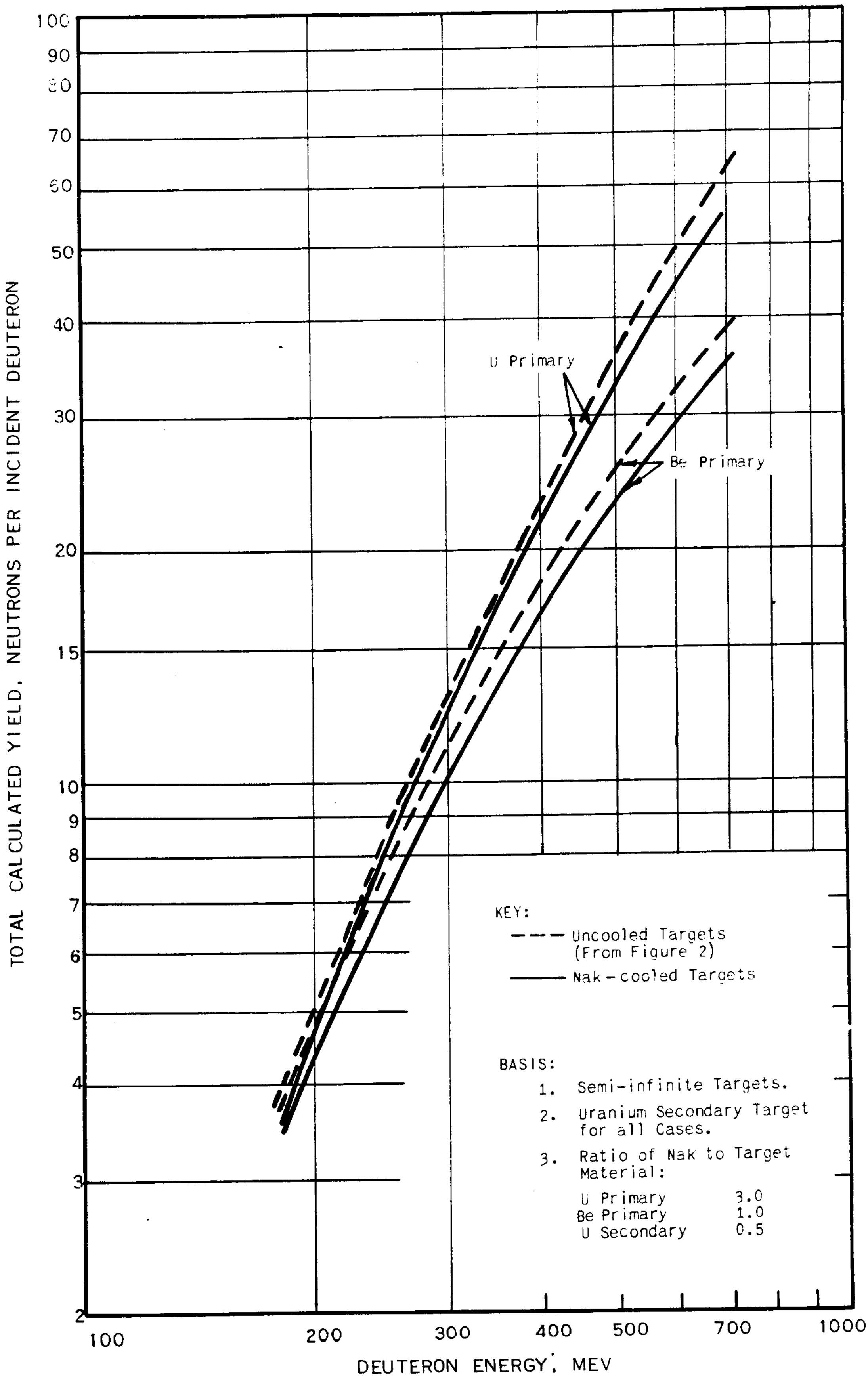


FIG. 3 - PREDICTED NEUTRON YIELDS FOR NaK - COOLED TARGETS

However, developments during the intervening period have resulted in greatly improved target concepts. These developments and their effect upon target design are discussed below.

Effect on Target of Changes in Accelerator Concept

The new accelerator concepts produce a deuteron beam of significantly smaller diameter than the A-12 design (perhaps 3 to 6 inches instead of 15 to 30 inches inside the drift tubes). This fact permits a smaller beam entry hole into the target, allows more efficient beam sweeping, and results in a smaller target volume with less inventory of depleted uranium, less shielding, a smaller target building, less expensive handling equipment, and generally lower investment costs.

Although not yet experimentally verified, the new accelerator concepts are also expected to produce a much more uniform distribution of beam current than that assumed for A-12. This would result in more uniform heat generation in the primary target and hence a more simplified target design with moderate additional decrease in target cost.

Other Developments

In addition to the effects of revised beam specifications outlined above, other developments have resulted in the following major changes in target design concepts.

(1) Light Element Primary

Theoretical work and some preliminary experimental data on beryllium and other light element primary targets indicated that they have significant advantages in reducing target size, as compared to a uranium primary, and in simplifying the handling and construction problem. This is because neutrons striking a light element primary lose energy at a lower rate - and therefore produce less heating per unit volume of primary - than in a uranium primary by roughly a factor of 10. The target cross-sectional area can be reduced correspondingly, with attendant investment cost savings. The light elements also are relatively good neutron reflectors, and permit more flexibility in relative placement of target components without excessive neutron losses. These advantages tend to offset the decreased yield from light metal primary targets compared to uranium targets.

(2) Liquid Metal Coolant

The use of light water in the primary and secondary targets had been shown experimentally to reduce the target yield appreciably, and present concepts call for the use of liquid metal coolants in these regions. The favor-

able experiences with Na and NaK systems at other installations since issue of LWS-12300 have increased confidence in the operability and reliability of liquid metal installations.

(3) In addition to the major factors enumerated above a number of other developments have been incorporated in recent target arrangements.

(a) Mechanical Design

The problem of stresses due to thermal strains in the containing structure of the primary target struck by the deuteron beam is better understood, and the resulting designs are simpler and probably cheaper to construct.

(b) Fuel Element Design

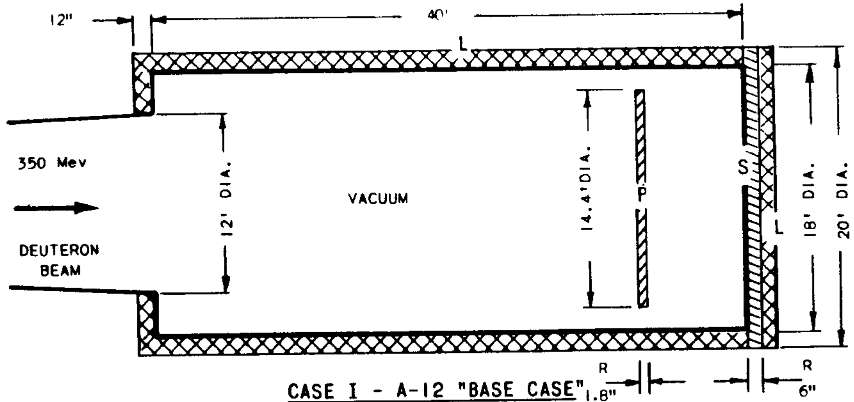
Fuel element fabrication, metallurgy and heat transfer studies have provided a basis for use of different fuel element geometries - - for example, spheres - which permit simplified handling features and a more compact target.

Analysis of available physics data has indicated that when using a light metal primary there may be a real advantage in omitting the lattice portion of a target and substituting an enlarged secondary surrounded by a reflector. These and other developments have been assessed in a preliminary way by developing conceptual designs and rough cost estimates for a number of alternative target arrangements embodying the features discussed above. These concepts are discussed in the following section.

4.3 Current Alternative Target Concepts

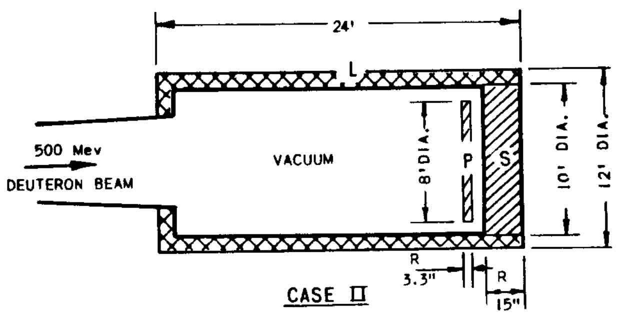
As a point of reference, the A-12 "base case" target concept reported in LWS-12300 is shown schematically as Case I in Fig. 4. For this concept, the primary and secondary targets are located at the rear of a vacuum tank which is surrounded by a uranium lattice. The proportions of the target components were chosen to give acceptably small neutron losses back through the beam entry opening and in structural material and to give reasonable cooling requirements. This target was designed for a 350-Mev, 500 milliampere deuteron beam.

Present target concepts are also illustrated schematically in Fig. 4 for comparative purposes. Each arrangement is scaled to give the same production rate as for the A-12 "base case", but with a 500-Mev deuteron beam at the required current. Actually, the best beam energy-current combination for each concept for a fixed production rate would be determined by an optimization study taking into account all elements of production cost - operating and investments costs for accelerator, target, processing, and



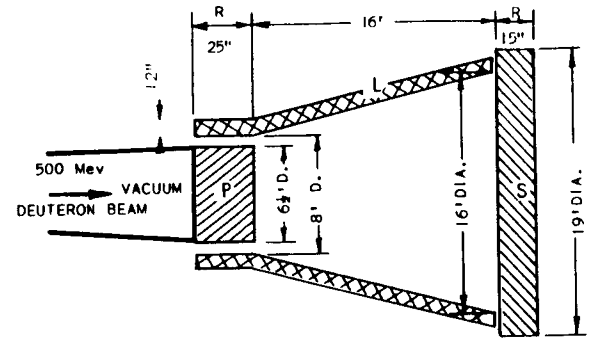
CASE I - A-12 "BASE CASE"

COMPONENT	MATERIAL	U INVENTORY	COOLANT
Primary	U	20 Tons	Water
Secondary	U	100 Tons	Water
Lattice	U	700 Tons	Water



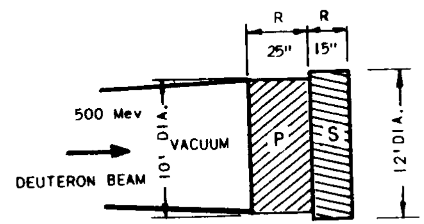
CASE II

COMPONENT	MATERIAL	U INVENTORY	COOLANT
Primary	U	11 Tons	Nak
Secondary	U	55 Tons	Nak
Lattice	U	260 Tons	Water



CASE III

COMPONENT	MATERIAL	U INVENTORY	COOLANT
Primary	Be	None	Nak
Secondary	U	228 Tons	Nak
Lattice	U	234 Tons	Water



CASE IV

COMPONENT	MATERIAL	U INVENTORY	COOLANT
Primary	Be, C, Nak*	None	Nak, Gas*
Secondary	U	60 Tons	Nak
Lattice	None	None	None

* Alternate Possibilities

LEGEND:
- P = Primary Target
- S = Secondary Target
- L = Lattice
- R = Thickness of Target Material (Excluding Coolant, Cladding, and Structural Materials).

FIG. 4 - COMPARISON OF CURRENT AND A-12 TARGET CONCEPTS

associated site facilities. The comparison at 500 Mev is made for simplicity, but it does serve to illustrate over-all design features of the recent concepts.

Case II uses the same general arrangement of components as Case I, but involves substitution of NaK for H_2O as coolant in the primary and secondary target components and reflects the advantages of the improved beam characteristics described earlier. The inventory of uranium is decreased by about one-half, and shielding and building investment costs are lower.

An arrangement using a light-metal primary is shown as Case III. The beryllium primary is located at the beam entry, since the stripped neutrons produced in Be are directed forward, and Be acts as a good reflector for neutrons in the space between primary and secondary. The secondary and the water-cooled lattice are no longer in a vacuum region, which decreases the amount of structural material required. Higher neutron fluxes, and consequently a smaller lattice area, can now be tolerated without excessive neutron losses. The secondary target is larger in diameter than the primary in order to receive neutrons coming directly from the primary with a half-angle divergence of 15 degrees.

Case IV also uses a light-metal primary, but in this case the primary and secondary are placed close together and there is no separate lattice. Neutrons leaving the secondary and entering the primary may be reflected and returned to the secondary where they are multiplied and productively captured. This target arrangement is less efficient than a type where a moderated lattice is used, in the sense that higher energy or current are required to obtain a given production rate. However, it does offer a target arrangement which is at least potentially simpler than the previous cases and preliminary cost estimates indicate that decreases in target investment and fuel inventory costs approximately balance the increased accelerator investment and operation costs. Inventories of depleted uranium required for each case are shown in Fig. 4.

Preliminary performance and cost estimates have been made for all of the new concepts illustrated, including variations of Case IV with beryllium, graphite, and NaK used as primary target materials. The tentative conclusion of this preliminary study is that plutonium costs for all of the new cases are the same within about 15 per cent, which is considered to be a smaller difference than the probable error of the estimates, and are substantially lower than for the A-12 design shown in Case I. A more detailed study--based on better experimental data and further analysis of performance, heat loads, and design features--is required before firm conclusions can be drawn regarding the relative merits of the new cases. However, there does appear to be an incentive for further investigation of the Case IV-type of target because of the relative simplicity of this concept. Case III was used for the cost evaluation.

The major conclusions, after reviewing the status of present target concepts in relation to the A-12 concept, are that developments since issue of LWS-12300 have resulted in major reductions in target costs, and have produced several new target concepts which are interesting alternative possibilities for plutonium production

4.4 Processing

The MTA processing phase of the A-12 project was based upon the premise that Purex technology as employed and tested at other sites for processing of reactor fuels would serve as the form and model for the MTA processing plant design. Time was not then available to make a basic study of the plant structure to adapt it specifically to MTA requirements. Laboratory and preliminary process design studies were at that time limited to minor process variations, such as those due to the use of other cladding material such as zirconium and the differing fission product distribution of irradiated target material. Processing capital cost estimates were obtained by direct scaling of the cost experience of prototype reactor separation plants on a capacity basis.

Recent technological developments have opened new design possibilities. The knowledge and art of equipment decontamination have been improved. Direct maintenance procedures have been investigated at ORNL and applied in the design of the Idaho Chemical Processing Plant. Alternatives in the Purex process have been investigated and tested, such as the substitution of "tail-end" treatment for "head-end" treatment steps. Later deliberation has defined certain differences in the design objectives and the process requirements for the MTA as compared to those of reactors. For example the uranium recovered from spent MTA fuel is not intended for diffusion plant feed and therefore need not meet the severe purity specification that apply to reactor fuels requiring re-enrichment. Since the tonnage throughput of an MTA may be relatively low as compared to recently installed reactor processing plants, a high incentive applies to design innovations which reduce investment costs and which avoid the heavy cost burden of a conventional "canyon" building.

These considerations have led to the concept of a considerably different structure for the MTA processing plant utilizing the same basic Purex chemistry. It appears that a considerably less expensive design can be obtained from a combination of various features that are individually minor. Elements of continuous process flow combined with elimination of head-end treatment would considerably abbreviate highly radioactive operations and reduce holdups. This abbreviation would make the segregation of these operations practical and advantageous. This segregation would in turn permit a practical employment of direct maintenance procedures in the remaining or major portion of the processing system. This approach has a firm technical

basis and is particularly appropriate to the potential versatility of an MTA since it would make future process alterations possible that could not be accomplished in a remote-maintenance plant where the system is "frozen".

With the highly radioactive portion of the processing plant considerably abbreviated by the above innovations, a new approach to maintenance of this equipment is also practical. The most economical design which would allow for maintenance with nearly uninterrupted operation is the construction of two complete lines of process equipment separated by shielding. This allows direct maintenance on one unit (after a suitable time for decontamination) while the other unit is operating. Thus most of the standard expensive appurtenances for remote maintenance may be eliminated. The design of the Idaho Chemical Processing Plant implies complete decontamination of equipment exposed to full fission product radioactivity, and future operating experience there should further define the solution to many of the problems involved.

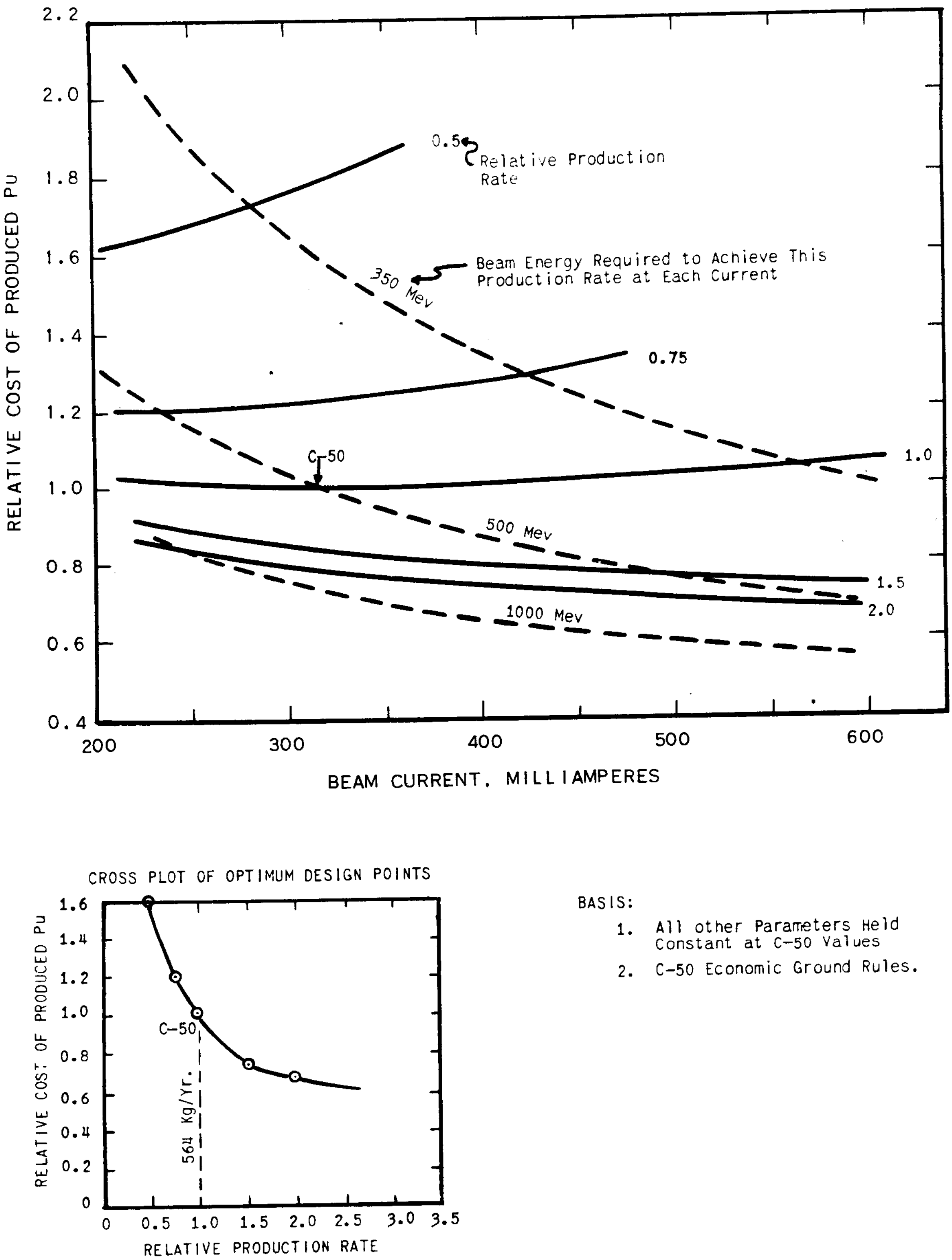
5. EFFECT OF MAJOR DESIGN PARAMETERS ON MTA PRODUCTION COSTS

This section deals with the effects of the important design factors on the unit cost of plutonium produced by an MTA process. The ranges of the various factors which have been evaluated frequently extend beyond the regions which have been explored up to the present. Results of these evaluations are not only a useful guide for further research and development, but form the basis for the C-50 concept.

5.1 Production Rate and Associated Beam Parameters

One of the most important design parameters affecting the cost of plutonium produced by the MTA process is the plutonium production rate. The production rate is in turn dependent upon the deuteron beam current and beam energy which must be selected in certain fixed combinations to give the desired production rate with a given target concept. The product cost is dependent not only upon the production rate, but upon the specific combination of these beam parameters used to achieve it. These relationships are shown in Fig. 5 with production rate normalized to the A-12 value of 564 kilograms of plutonium per year.

It is apparent from Fig. 5 that increases in production rate appreciably reduce the product cost. This effect is particularly prominent at production rates lower than that selected for the A-12 concept. Thus, it is desirable to build a relatively large-scale production plant in order to avoid excessive cost of the produced plutonium.



BASIS:

1. All other Parameters Held Constant at C-50 Values
2. C-50 Economic Ground Rules.

FIG. 5 - EFFECT OF PRODUCTION RATE AND BEAM PARAMETERS ON PRODUCT COST.

The optimum combination of beam energy and beam current for a given production rate is different for the various production rates shown in Fig. 5. For the A-12 production rate, the product cost is not greatly dependent on the beam characteristics selected (within the range covered by Fig. 5), but product cost appears to be optimized at a beam energy of approximately 500 Mev. However, at lower production rates, minimum product cost is obtained by selecting appropriate combinations of low currents and high energies; for higher production rates, increase of beam current at the expense of beam energy optimizes the design. This effect is basically due to the slower rate of increase in neutron production per incident deuteron as the beam energy is increased.

5.2 Accelerator Design Parameters

Two of the most important parameters involved in accelerator design are the frequency and the voltage gradient. The vessel diameter is largely determined by the selection of its operating frequency, and the vessel length is largely determined by the selection of its operating voltage gradient. The expected total cost of MTA produced plutonium has been estimated for reasonable ranges of these design parameters.

The major changes which result from an increase in accelerator frequency are a smaller diameter vessel and reduced rf skin losses. These changes reduce both investment and operating costs and hence result in the reduction in product cost with increase of frequency which is shown in Fig. 6. Product cost decreases appreciably with an increase in frequency from 12 to 50 megacycles, and decreases more slowly with further increases in frequency as shown in Fig. 6. Technical feasibility and oscillator tube development place a present upper limit on frequency at about 50 megacycles, but further development should allow the use of higher frequencies with the attendant cost reduction.

The major changes which result from an increase in accelerator voltage gradient are a shorter vessel and increased rf skin losses. These changes decrease the investment cost and increase the operating cost, resulting in the variation in product cost with voltage gradient shown in Fig. 7. These opposing effects of variation in voltage gradient result in a minimum product cost which is obtained at a voltage gradient of about 0.35 to 0.6 megavolts per foot of vessel length. The use of voltage gradients higher than this would increase the product cost. It is fortuitous that the economically optimized voltage gradient appears to be highly feasible from an operating standpoint in that spark-free operation should be attainable with reasonable injection energies.

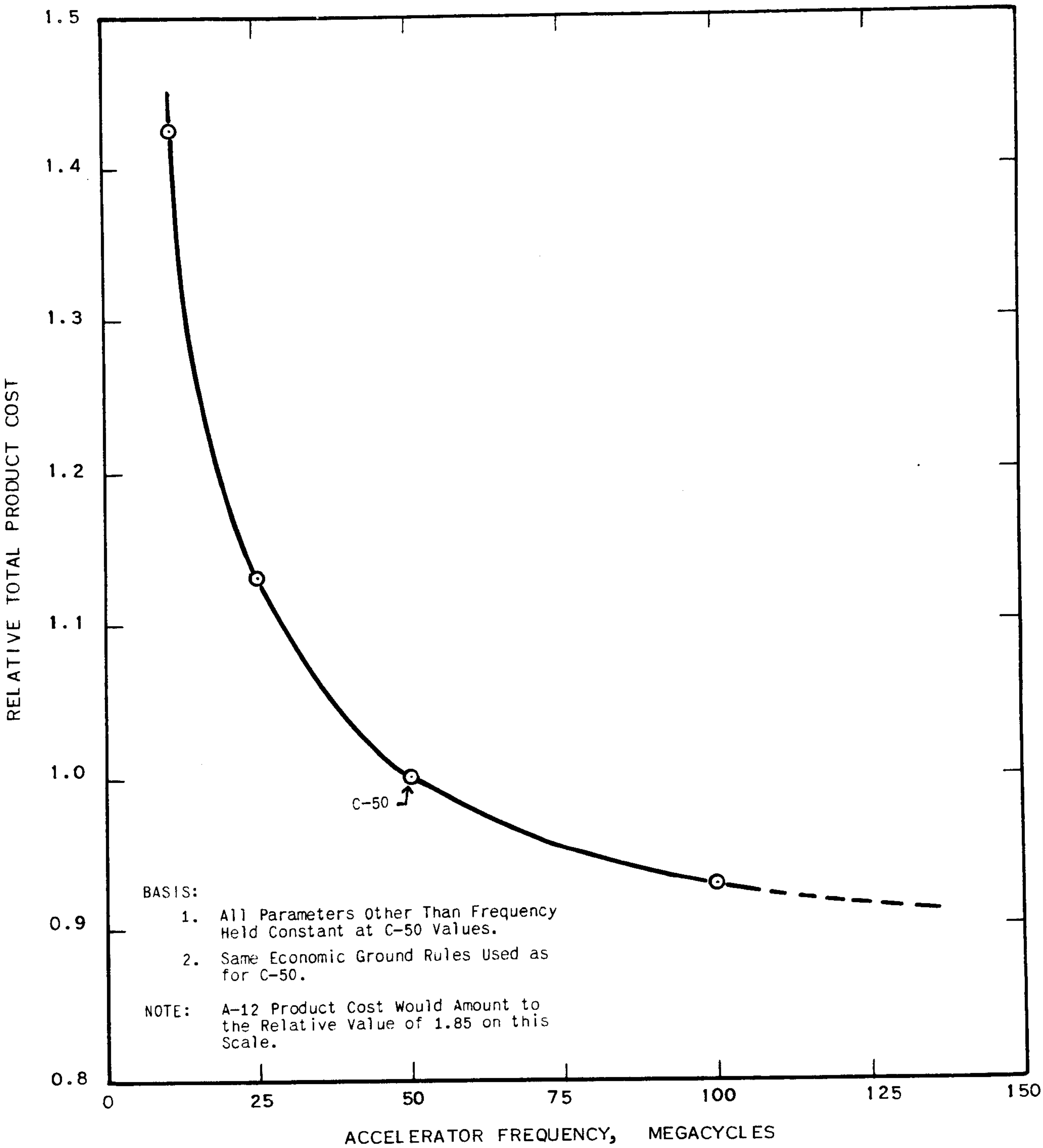


FIG. 6 - EFFECT OF ACCELERATOR FREQUENCY ON COST OF MTA - PRODUCED PLUTONIUM.

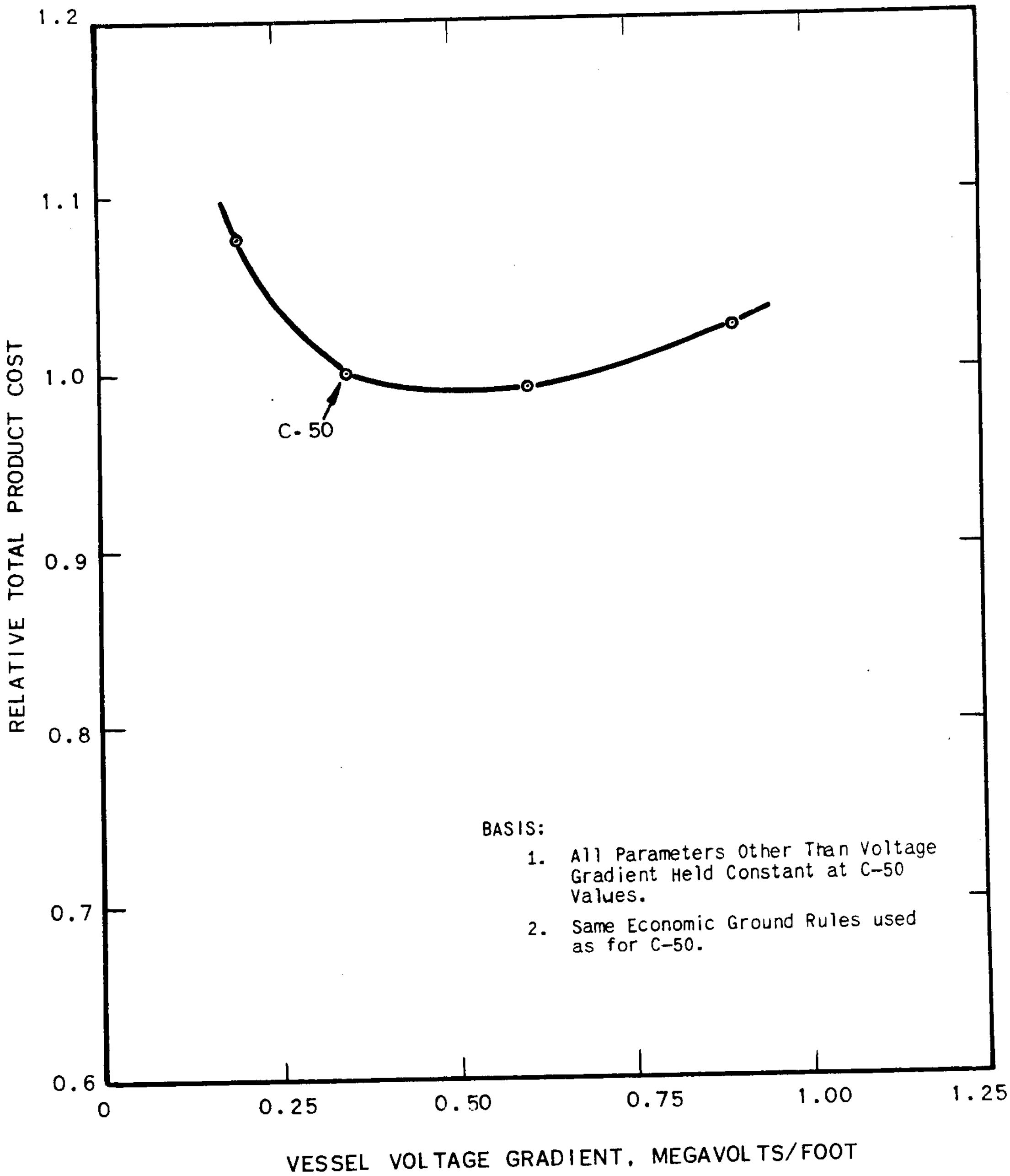


FIG. 7 - EFFECT OF ACCELERATOR VOLTAGE GRADIENT ON COST OF MTA - PRODUCED PLUTONIUM

5.3 Target Design Parameters

The major target design parameters are the geometrical arrangement, choice of primary target material, choice of coolants, and the processing level. Conceptual designs based upon various combinations of these parameters were presented in Section 4.3 of this report, where it was pointed out that the cost of produced plutonium would be approximately the same for each of the present target concepts. However, this conclusion must be regarded as preliminary inasmuch as it is based upon very limited experimental data and approximate cost estimates.

While total production costs are nearly equal for all the present target concepts, the breakdown of the costs is significantly different. In general, the targets using a surrounding lattice of depleted uranium are more efficient than those without the lattice and consequently require lower accelerator investment and operating costs. However, these savings are offset by higher target investment and operating costs. The target concepts which include a lattice have received more study and the characteristics of these concepts are consequently better understood. Thus, only these concepts were considered for inclusion in the C-50 plant concept presented in the next section of this report. However, the greater simplicity of the target concepts which omit the lattice offers greater potential operating reliability and greater ease of expansion of production rate, factors which could not be included in the economic analysis. Thus, these target concepts offer real incentives for further research and development effort.

5.4 Chemical Processing Design Parameters

The changes in MTA processing plant requirements from the early A-12 concept which were discussed in the preceding section have greatly reduced the cost of this portion of the operation. Further experimental data and operating and maintenance experience at other installations in this field should point out additional cost-saving design changes. However, since chemical processing costs contribute less than ten per cent to the total MTA product cost, further cost reductions in this field will have a relatively minor effect on product cost.

5.5 Feasibility of Power Recovery

A potential reduction in MTA production costs exists in the recovery of power from the heat released in the target. Since power costs are an appreciable portion of the MTA operating costs, the over-all economics of various plant concepts could be altered considerably by the installation of power recovery facilities. Such facilities would mean less emphasis on the cost and availability of power in site selection, and would hence mean a relatively greater freedom of site location.

The estimated fraction of the accelerator power requirement which might feasibly be recovered through the installation of power recovery facilities for a NaK-cooled target ranges from 50 to 70 per cent increasing with increases in beam energy and current This estimate is based on present accelerator and target concepts and assumes that the target could be designed to allow an outlet coolant temperature of 800-1000F in order to obtain a power plant thermal efficiency of about 30 per cent. While such an assumption appears to be reasonable, the concept has not been investigated in detail.

In order to recover the above-mentioned fraction of the accelerator power input, installation of additional facilities would be required over those necessary for target cooling without power generation. Both systems would require similar target NaK cooling systems and intermediate heat exchangers; the additional facilities required would include a conventional turbo-generator plant and steam generating heat exchangers in place of NaK-water heat exchangers.

For the C-50 plant concept discussed in the next section of the report these additional facilities are estimated to cost an additional 20 million dollars, and would recover 55 per cent of the 300 megawatt accelerator power input. This investment would be competitive with outside power costs of approximately 3.5 mills per kwh. Since this power cost is somewhat below the expected MTA power cost, a small economic incentive is indicated. Although this result is based upon preliminary cost estimates, it is important to note that 75 per cent of the incremental expenditure is for conventional turbo-generator power plant equipment for which reasonably accurate cost data are available.

Even though the economic incentive for the installation of power recovery facilities may not be large, other factors may justify their installation. The accelerator could conceivably be started at about one-half its rated power input with the net external power, and the beam current gradually increased as power recovered from the target is fed back. Thus both maximum net power demand and net energy requirements from external sources would be reduced. More freedom in site location would then be available as outside power costs would assume less importance in the site selection. In fact, if new power generating facilities would be required to meet the net power requirements, these could feasibly be installed on the site and integrated with the power recovery facilities.

6. TYPICAL CURRENT CONCEPT OF MTA PRODUCTION PLANT

To facilitate presenting a preliminary economic evaluation of the latest MTA developments which have been discussed in the previous sections of this report, a new typical concept, herein referred to as C-50, has been prepared. The C-50 concept is based upon specifications which are believed to be reasonable and attainable in view of present data and experience.

Many of the specifications are extrapolations from performance which has actually been demonstrated experimentally, but they represent the best technical judgment available as to operating conditions which can be achieved in the short-range future as a result of the presently authorized MTA research and development effort. However, under these circumstances there is a distinct possibility that these specifications might change as more experimental information is developed. Where possible to do so without undue extrapolation from proven performance, design paramaters have been selected so as to result in minimum product cost. However, detailed design studies, such as those which would be made preparatory to actual construction of an MTA plant, would undoubtedly result in some revision of these specifications in order to optimize performance, operability, and costs.

In summary then, the C-50 concept presented herein represents the present day best judgement of an MTA production plant which could be built and operated as predicted.

In this section of the report, the present C-50 concept will be compared to the earlier MTA plant as presented in a June, 1952 informal report (Document No. LWS-24428) and designated the A-12 concept. This informal report supplemented a January, 1952 MTA report (Document No. LWS-12300) which gave more detailed design specifications for A-12.

6.1 Criteria for Selection

A brief discussion of the factors which entered into the selection of some of the more important design parameters for the C-50 concept is given in the following subsections.

6.11 Site Location

The site for the C-50 concept was assumed to be Weldon Spring, Missouri. It is recognized that this assumption somewhat penalizes the MTA concept when comparing it with processes located at an established site where auxiliary facilities and services can be shared with the over-all site operations. However, the choice was made to facilitate a more direct

comparison with the earlier A-12 concept and to take advantage of basic cost and technical data already established for the Weldon Spring site.

6.12 Production Rate and Associated Beam Parameters

An annual production of 564 kilograms of plutonium has been selected for the C-50 concept. This is the same production rate used for the A-12 concept, and the selection facilitates comparison of the two concepts. To achieve this production rate, a combination of beam parameters of 500-Mev energy and 320 milliamperes current was chosen for the C-50 concept. This compares with the beam energy of 350 Mev and the beam current of 500 milliamperes used for A-12. The present selection represents a technically reasonable and economically optimized choice as was shown by Fig. 5.

6.13 Accelerator Design Parameters

An increase in frequency from 12 megacycles for A-12 to 50 megacycles for C-50 represents the most significant difference in the two concepts for the accelerator proper. As was pointed out in references to Fig. 6, a considerable cost reduction has been achieved by this increase in frequency. Although further cost reductions would result from additional increases in frequency, 50 Mc has been specified for C-50 since power amplifier tubes are available which have been proven capable of operation at this but not at higher frequencies.

A voltage gradient of 0.25 megavolts per foot of vessel length has been selected for the lowest and highest energy sections of the C-50 accelerator, with 0.35 megavolts per foot of vessel length for the intermediate sections. This compares with a uniform voltage gradient of 0.375 megavolts per foot of vessel length used for A-12. As was shown by Fig. 7, no appreciable economic incentive exists for the selection of a higher voltage gradient, and the present value is expected to allow spark-free operation at reasonable injection energies.

6.14 Target

A beryllium primary, uranium secondary and uranium lattice have been selected for the C-50 target. NaK-cooling of the primary and secondary and water-cooling of the lattice have been specified. This is the Case III target concept described in Section 4.3 of this report. As was discussed in Section 4.3, this target represents a significant improvement over the entirely water-cooled uranium target used for A-12. Although the target selected is not necessarily better than some of the other current target concepts, it was chosen because the basic production characteristics of the system have been experimentally and theoretically studied in greater detail than for some of the other present target concepts.

6.15 Chemical Processing

The chemical processing plant selected for C-50 is one which is specifically designed to meet the requirements of an MTA plant. Such a processing plant incorporates the recent developments discussed in Section 4.4. of this report and represents a considerable simplification from the plant included in the A-12 concept. An alternative possibility is the sharing of a portion of the capacity of a large conventional processing plant if such were available. This alternative would result in essentially the same processing costs.

6.2 Summary Description

A brief description is included here of the C-50 concept as now envisioned for estimating purposes. A more detailed description is included later in the report as Appendix "A".

The site consists of about 8,500 acres of partially wooded terrain for which the Missouri river forms one boundary. Although the main cooling water source is from wells, their proximity to the river ensures a reliable supply.

The beam injection system having about 2 Mev of energy will embody a combination of direct current and radiofrequency acceleration. The accelerator proper is approximately 2640 feet long. It involves a vacuum vessel of this length consisting of 26 smaller vessels connected end-to-end. These vessels are of copper-clad steel construction and range from 14 feet to 11 feet in diameter. Evacuation of the vessel is accomplished by means of mechanical roughing pumps and linear diffusion pumps. The accelerator is housed and shielded by a concrete structure. Auxiliary equipment is housed in a building attached to and extending the full length of one side of the shielding.

Radiofrequency power is supplied to the cavity through 216 transmission lines, each of which is connected to a power amplifier. These power amplifiers are controlled by 24 driver amplifiers making a total of 240 amplifiers. The 240 amplifiers are supplied by 24 ignitron rectifiers which are fed by the ac power source. A schematic power flow diagram is given in Fig. 8.

Design parameters and specifications for the accelerator proper are given in Table IV. A typical section of the accelerator is shown in Fig. 9.

The target consists of essentially three sections arranged in the form of a hollow truncated cone about 25 feet long with its axis horizontal. The small end, about 8 feet in diameter, is the beryllium primary

target which receives the high energy deuterons from the accelerator. The neutrons resulting from this bombardment in turn bombard the 19 ft diameter large end of the cone which is the uranium secondary target. Stray neutrons are captured in the wall of the conical section which is the uranium lattice. Fig. 10 shows a schematic neutron balance for the various target sections. The primary and secondary targets are cooled with sodium-potassium alloy (NaK). This radioactive NaK circuit is in turn cooled by a second NaK circuit which is water-cooled. The lattice is water cooled. The uranium in the lattice and secondary target is in the form of small spheres to facilitate fuel handling. Plutonium is produced in these two sections in approximately equal quantities. Figure 11 shows a flow diagram for the uranium and plutonium through the target and processing area. The target proper, NaK heat exchangers, and fuel handling facilities are enclosed in a concrete structure which serves as both shielding and housing. Design parameters and specifications pertinent to the target design are shown in Table V. Figure 12 shows an isometric cutaway view of the target proper, and Figs. 13 and 14 show cross-sectional views of the target area.

Chemical separation of plutonium, uranium, and wastes is to be accomplished by a modified Purex process plant, described in Appendix A-5.

TABLE IV

DESIGN PARAMETERS & SPECIFICATIONS C-50 ACCELERATOR

Basic Parameters	
Frequency	50 megacycles
Beam Current	320 milliamperes
Injector Operation	Continuous wave
Beam Energy Output	500 million electron volts
Beam Energy Input From Pre-accelerator	2 million electron volts
Electric Field Gradient (cell gradient)	
Mode cells 1, 2 and 26	0.25 million volts per foot
Mode cells 3 through 25	0.35 million volts per foot
Drift Tube Type	Mark I type
Drift Tube Outside Diameter	2.05 feet (all drift tubes)
Design Details	
Total length of Accelerator (not including mode cell interconnections)	2640 feet
Total overall length of Accelerator building	3100 feet
Average Particle energy gradient	0.188 million electron volts per foot
Number of Mode Cells	26
Average Length of Mode Cell	100 feet
Maximum Cavity Diameter	14.1 feet
Minimum Cavity Diameter	11.0 feet
Number of Drift Tubes	368
Maximum Drift Tube Length	6.15 feet
Minimum Drift Tube Length	11.6 inches
Minimum Gap Length	3.8 inches
Drift Tube inside Diameter	3.0 inches minimum 6 to 9 inches maximum
Power Requirements	
Radiofrequency skin losses	41 megawatts
Radiofrequency beam power load	160 megawatts
Other radiofrequency losses	15 megawatts
Total radiofrequency power required	216 megawatts
Direct Current Power Supply for Radiofrequency system operating at 75 per cent efficiency	288 megawatts
Alternating Current Power at 96 per cent efficiency for direct current power supply to rf system	300 megawatts

TABLE IV (Cont'd)

DESIGN PARAMETERS & SPECIFICATIONS C-50 ACCELERATOR

Total plant Power for all Services	335 megawatts
Vacuum Requirements	
Diffusion Pumps	
3 x 16 foot rectangular pumps	28 pumps
Kinney Pumps	26 pumps at 702 cu ft per minute 2 pumps at 311 cu ft per minute
Liquid Nitrogen Consumption	3850 pounds per hour
Accelerator Cooling Requirements	
Distilled water, circulating	54, 100 gallons per minute
Distilled water, makeup at 4 per cent	2, 200 gallons per minute
Treated water, circulating	53, 000 gallons per minute
Treated water, makeup at 4 per cent	2, 100 gallons per minute

TABLE V

DESIGN PARAMETERS AND SPECIFICATIONS - C-50 TARGET				
ITEM	UNITS	PRIMARY	SECONDARY	LATTICE
1. Description		Be plates	Unclad ½" dia U spheres	Al-clad 2" dia U spheres
2. Coolant		NaK(78% K)	NaK (78% K)	H_2O
3 Total Thickness	inches	36	25	12
4. Size		8 ft dia	19 ft dia	8' to 16' dia truncated cone 20' long
5 Inventories		6450 lbs Be	228 tons U	234 tons U
6. Processing Level	gPu/ton U	--	1000	700
7. Fuel Throughput	tons/year	(1 yr estimated life)	283	404
8 Heat Liberated				
(a) Total Heat	Mw	130	420	275
(b) Max. Power Density	kw/in^3	36.5	2.7	1.2
(c) Peak to Average Power Density	--	20/1 (unswept)	3.5/1	4/1
9. Cooling Data				
(a) Max. Heat Flux	kw/in^2	3.38	0.23	0.40
(b) Max. Fuel Surface Temperature	°F	750°	< 1000°	< 1000°
(c) Coolant Flow Rate	gpm	10,500	52,000	53,000
(d) Coolant Inlet Temperature	°F	150°	150°	100°
(e) Coolant Outlet Temperature	°F	610°	450°	135°

43

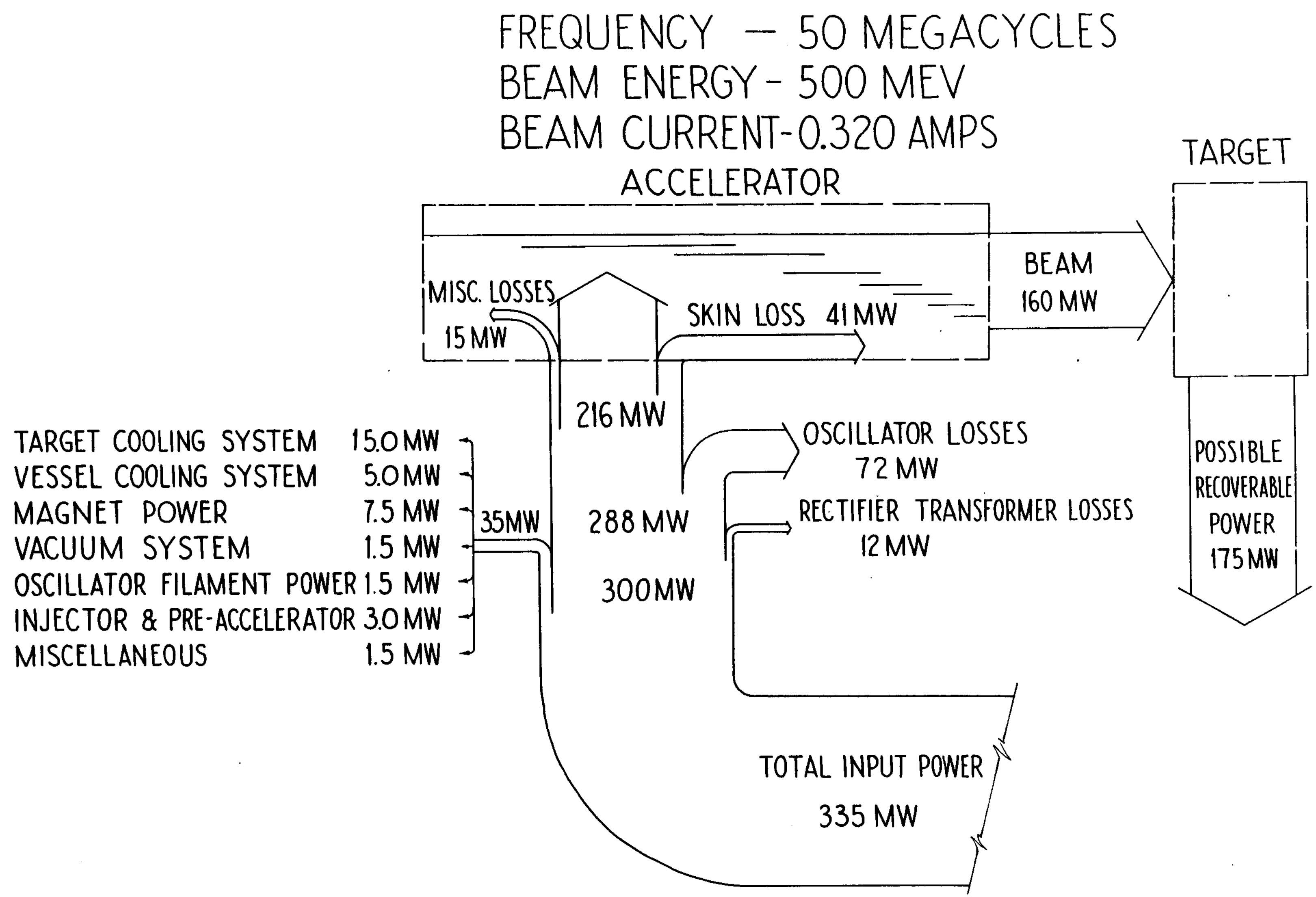


FIG. 8 - SCHEMATIC POWER FLOW DIAGRAM

002 042

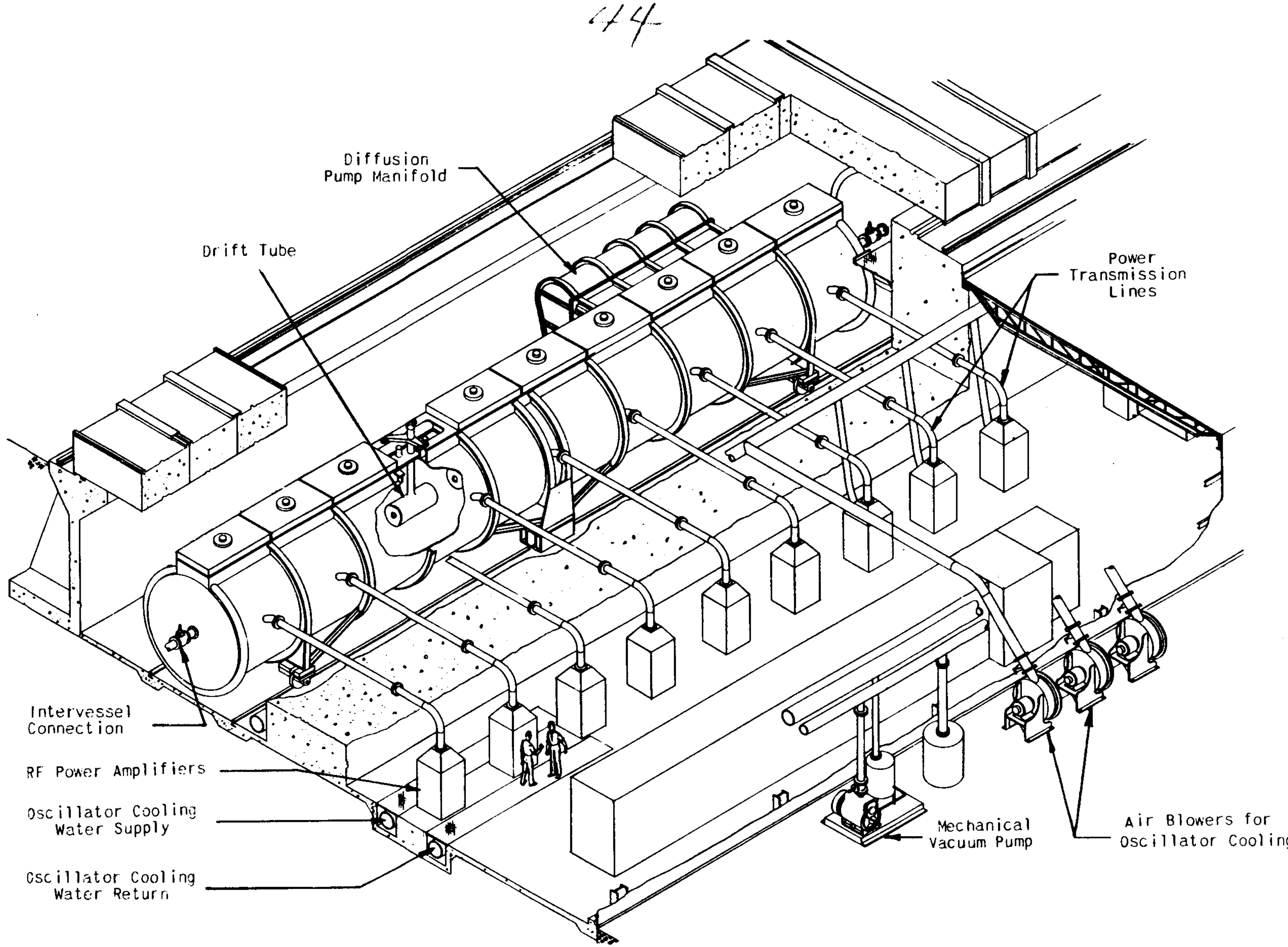


FIG. 9 - ISOMETRIC OF TYPICAL ACCELERATOR VESSEL - C-50 CONCEPT.

NOTE
Numbers Expressed in Gram-mols per Operating Day.

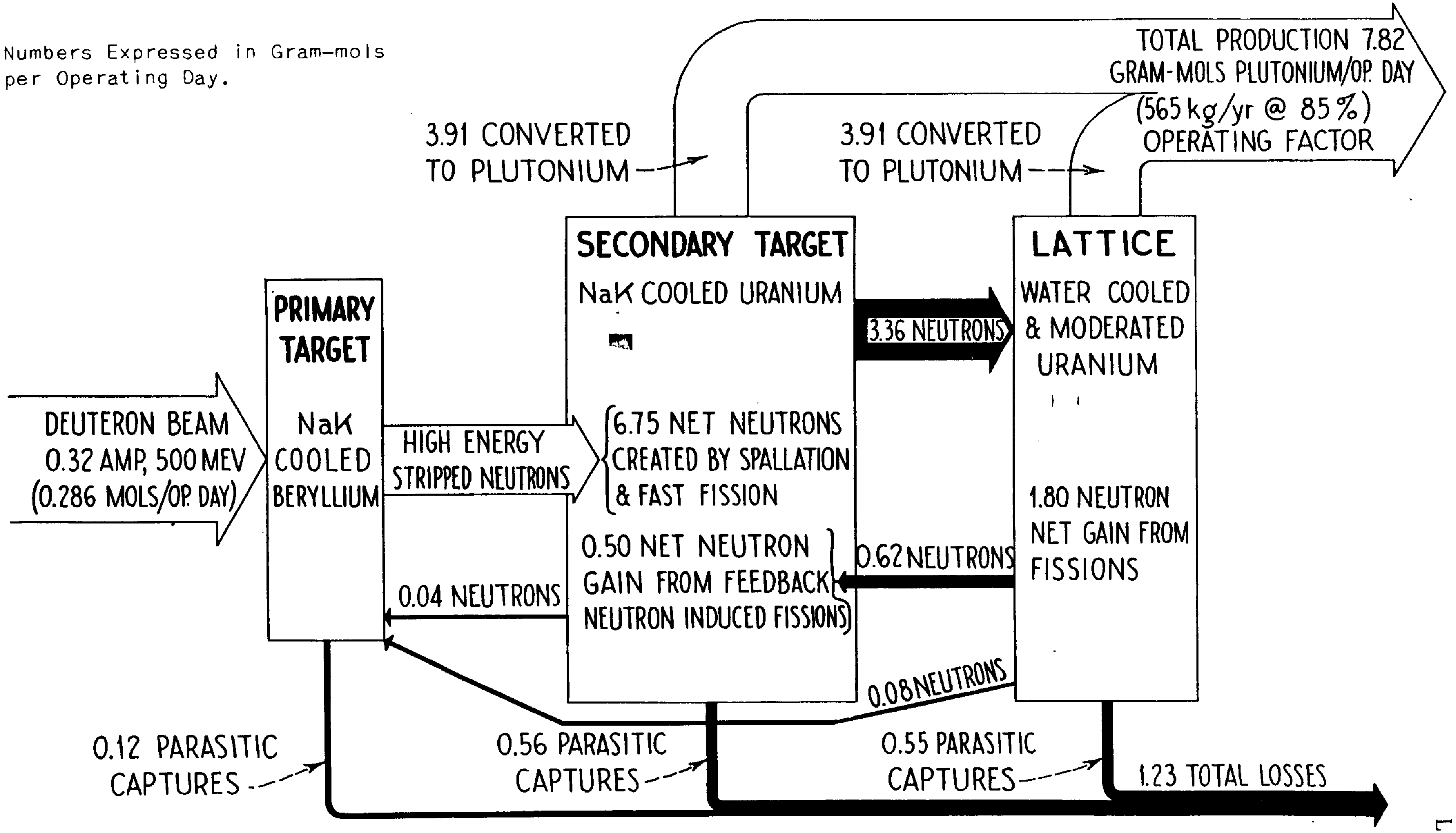


FIG. 10 - NEUTRON BALANCE FOR C-50 TARGET

46

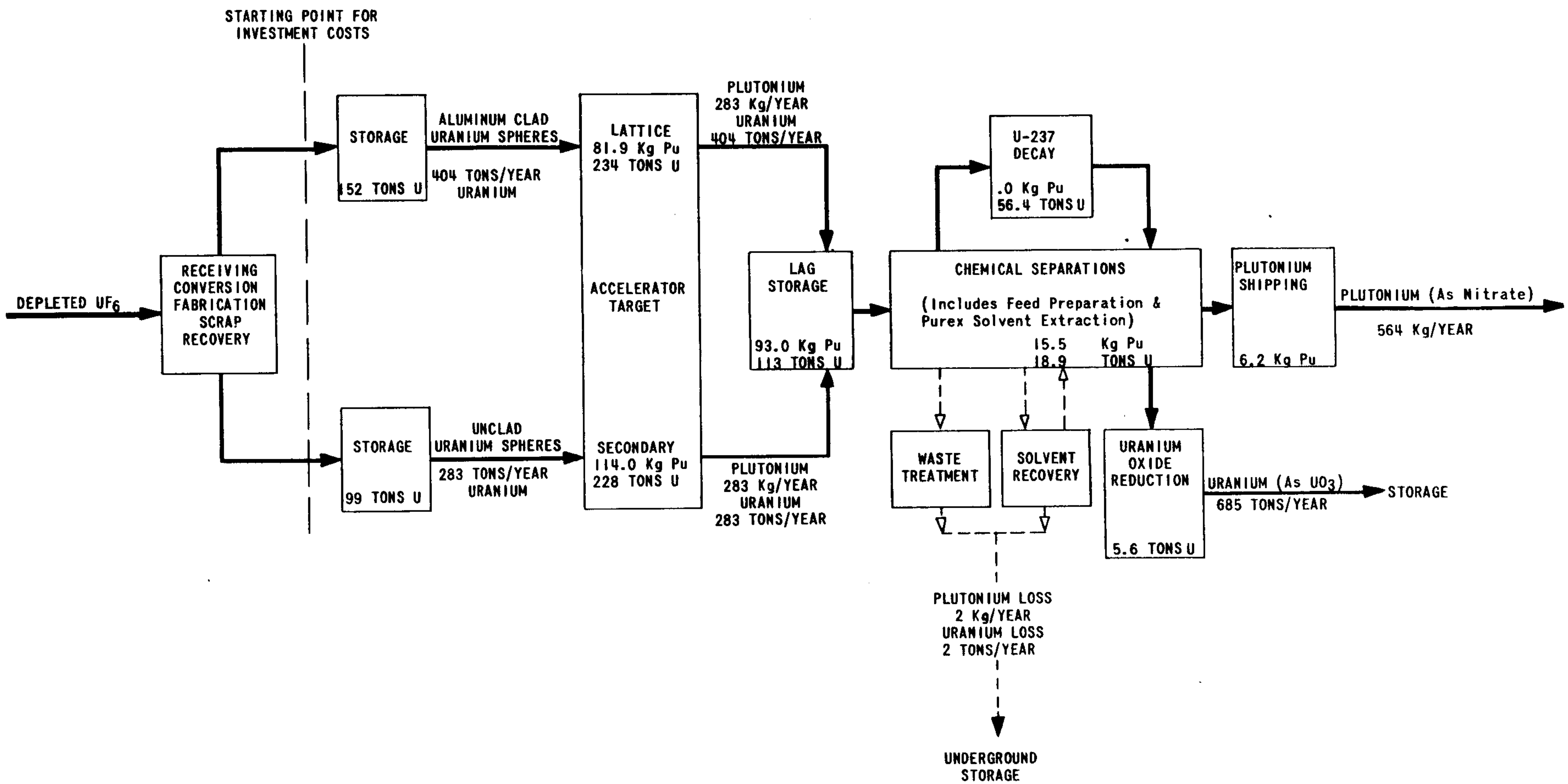
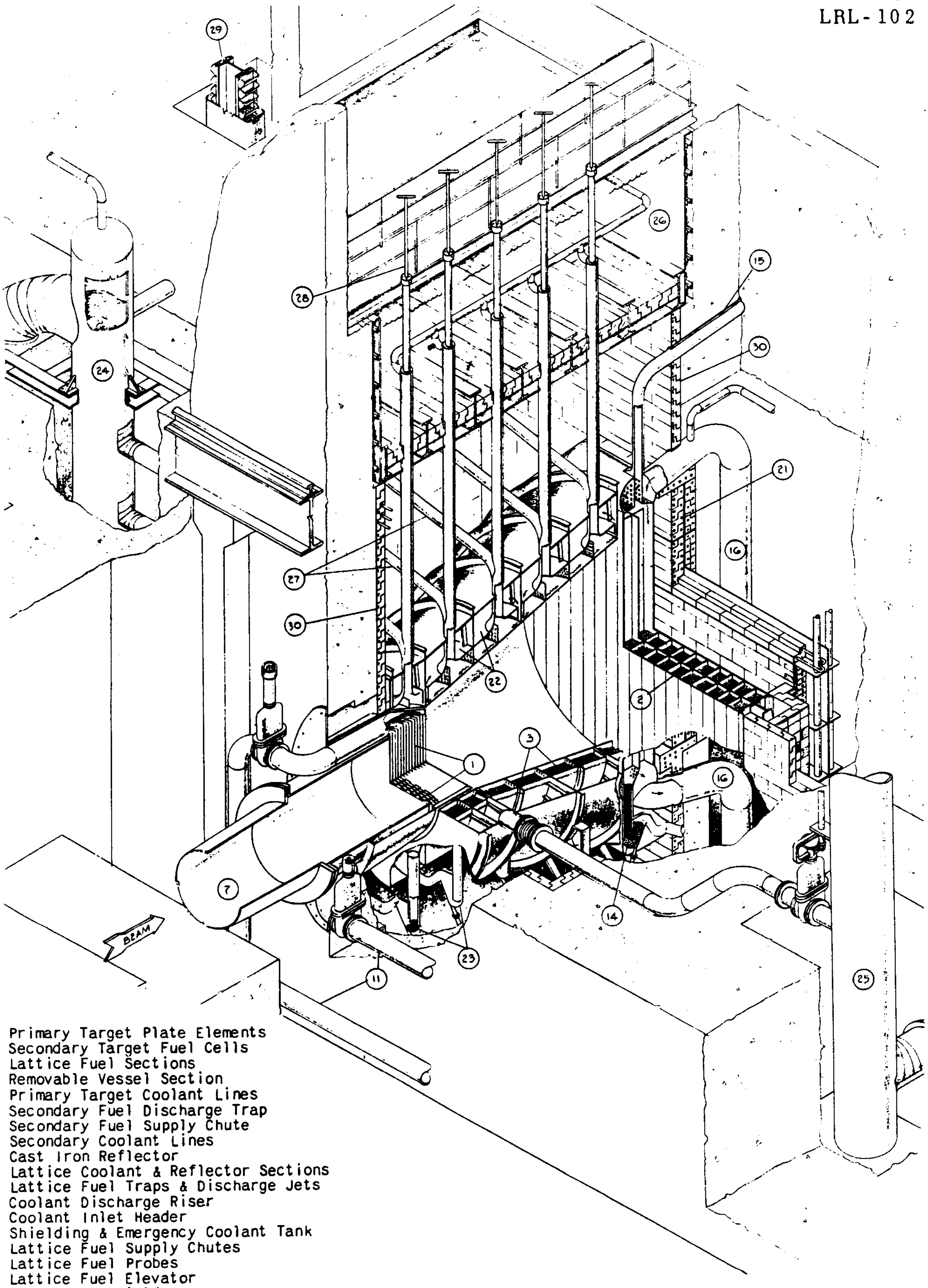


FIG. 11 - FLOW AND INVENTORY DIAGRAM OF SOURCE AND FISSIONABLE MATERIALS - C-50 CONCEPT.



1 Primary Target Plate Elements
2 Secondary Target Fuel Cells
3 Lattice Fuel Sections
7 Removable Vessel Section
11 Primary Target Coolant Lines
14 Secondary Fuel Discharge Trap
15 Secondary Fuel Supply Chute
16 Secondary Coolant Lines
21 Cast Iron Reflector
22 Lattice Coolant & Reflector Sections
23 Lattice Fuel Traps & Discharge Jets
24 Coolant Discharge Riser
25 Coolant Inlet Header
26 Shielding & Emergency Coolant Tank
27 Lattice Fuel Supply Chutes
28 Lattice Fuel Probes
29 Lattice Fuel Elevator
30 Cold-Wall Shield

FIG. 12 - ISOMETRIC CUTAWAY OF C-50 TARGET.

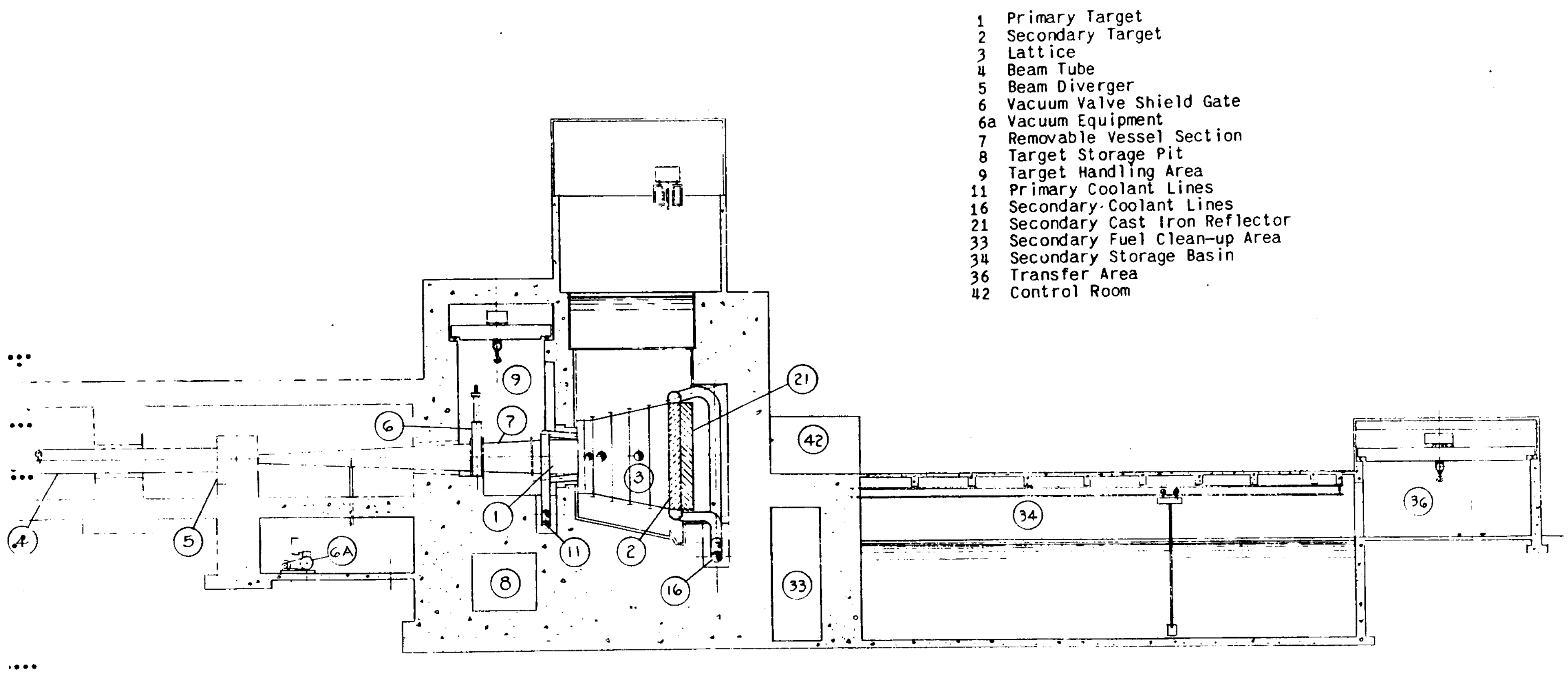


FIG. 13 - LONGITUDINAL CROSS SECTION OF C-50 TARGET AREA.

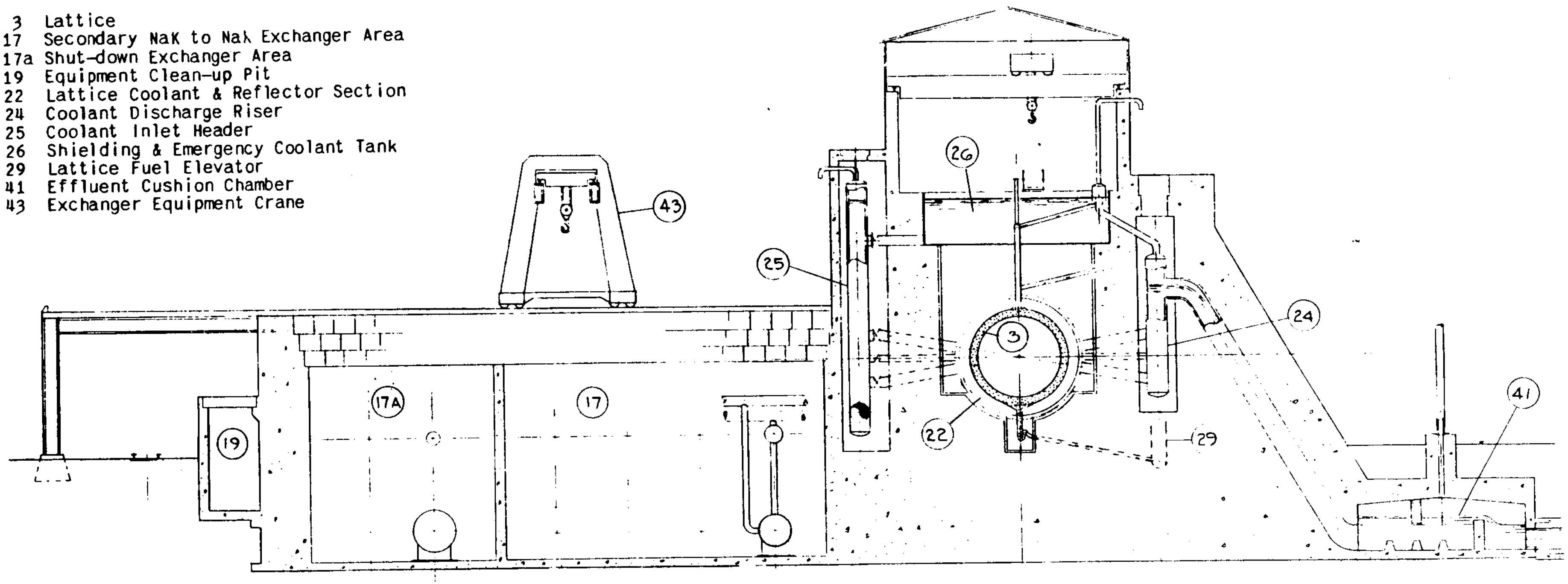


FIG. 14 - TRANSVERSE CROSS SECTION OF C-50 TARGET AREA.